Geomorphology 116 (2010) 67–76

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Magnitude–frequency relationships of debris flows — A case study based on field surveys and tree-ring records

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A R T I C L E   I N F O

Article history:
Received 30 July 2009
Received in revised form 14 October 2009
Accepted 15 October 2009
Available online 24 October 2009

Keywords:
Debris flows
Tree-ring analysis
Dendrogeomorphology
Deposits
Sediment
Triggering events
Permafrost
Climate change
Swiss Alps

A B S T R A C T

Debris-flow activity in a watershed is usually defined in terms of magnitude and frequency. While magnitude–frequency (M–F) relations have long formed the basis for risk assessment and engineering design in hydrology and fluvial hydraulics, only fragmentary and insufficiently specified data for debris flows exists. This paper reconstructs M–F relationships of 62 debris flows for an aggradational cone of a small (<5 km^2), high elevation watershed in the Swiss Alps since A.D. 1863. The frequency of debris flows is obtained from tree-ring records. The magnitude of individual events is given as *S, M, L, XL*, and derived from volumetric data of deposits, grain size distributions of boulders, and a series of surrogates (snout elevations, tree survival, lateral spread of surges). *Class S* and *M* debris flows ($<5\times10^3$ m^3) encompass a typical size of events and have mean recurrence intervals of 5.4 (SD: 3.2) and 7.4 years (SD: 6.7), respectively. *Class XL* events (10^4–5×10^4 m^3) are, in contrast, only identified three times over the past 150 years, and major erosional activity on the cone was restricted to two of these events in 1948 and 1993. A comparison of results with hydrometeorological records shows that *class L* and *XL* events are typically triggered by advective storms (rainfall >50 mm) in August and September, when the active layer of the rock glacier in the source area of debris flows is largest. Over the past ~150 years, climate has exerted control on material released from the source area and prevented triggering of *class XL* events before 1922. With the projected climatic change, permafrost degradation and the potential increase in storm intensity are likely to produce "*class XXL*" events in the future with volumes surpassing 5×10^4 m^3 at the level of the debris-flow cone.

1. Introduction

Debris-flow activity within a given area can be defined in terms of frequency (i.e., the number of debris-flow occurrences per unit time; also known as temporal frequency) and magnitude (i.e., the size of an event; Van Steijn, 1996; Hungr et al., 2005). The determination of temporal occurrence and size of debris flows is not only of crucial importance for hazard and risk assessment, but also for landscape evolution, landuse planning or the design of torrent control (Hungr et al., 1984; Rickenmann, 1999; Hungr et al., 2008; Mao et al., 2009). In the Alps, debris flows represent one of the most important hazards (Bloetzer and Stoffel, 1998; Marchi and D'Agostini, 2004; Jakob and Hungr, 2005) and devastating events caused fatalities and severe damage to infrastructure and transportation corridors in 1987 (Rickenmann and Zimmermann, 1993), 2000 (BWG, 2002), and 2005 (Habersack and Krapesch, 2006; Bezzola and Hegg, 2007).

Although debris flows are recognized as a frequently occurring and destructive phenomenon, relatively few studies have addressed the magnitude–frequency (M–F) aspects compared to the large number of works on debris-flow rheology and dynamics (Iverson, 1997; McArdell et al., 2007). The small number of M–F studies also contrasts sharply with the situation in analytical hydrology and fluvial hydraulics, where M–F relations have long formed the basis for engineering design (Bovis and Jakob, 1999). For the Swiss Alps, records on pre-1987 debris flows are not readily available, resulting in very fragmentary data on return intervals of debris flows. In addition, magnitude is, as in other Alpine environments, insufficiently specified (Van Steijn, 1996; Carrara et al., 2003; Marchi and D'Agostini, 2004). We also observe an important deficiency of torrents and gullies that have been monitored over sufficiently long periods of the past, despite recognition that debris flows possess much greater erosive and hazard potential than do flood processes (Pierson, 1980).

Several authors have derived M–F relationships for debris flows in the past (Hungr et al., 2008). Most studies used indirect dating methods, such as stratigraphic techniques (Blair and McPherson, 1998; Blair, 1999), lichenometric methods (Rapp and Nyberg, 1981; Innes, 1983, 1985; Helsen et al., 2002), or aerial and LiDAR photography interpretation (Jakob et al., 2005; Scheidl et al., 2008).

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doi:10.1016/j.geomorph.2009.10.009

In addition, the analysis of volumes triggered from the source area and material entrained along the flow path (Eaton et al., 2003; Hungr et al., 2005) or the design of empirical or statistical equations (Marchi and D'Agostini, 2004) have been used to determine magnitude and frequency of debris flows.

On forested cones, tree-ring series of trees affected by debris flows can be analyzed to gather data on past events or to complete records from written sources (Hupp, 1984; Strunk, 1991, 1997; Baumann and Kaiser, 1999; Stoffel et al., 2006). Research focused on (i) spatio-temporal patterns of debris flows on cones (Bollschweiler et al., 2007; Stoffel et al., 2008a), (ii) the study of debris-flow activity in currently abandoned channels (Bollschweiler et al., 2008), or (iii) the investigation of meteorological conditions triggering debris flows (Stoffel and Beniston, 2006). Results from tree-ring analyses have, in contrast, not been coupled with data from field surveys so far to analyze volumes left on cones during particular events or to define M–F relationships of debris flows.

In an attempt to foster the understanding of M–F relationships of debris flows, this paper sheds light on 150 years of debris-flow activity on a cone in the Swiss Alps by coupling results from tree-ring analyses with field survey data and sedimentological records. The specific objectives of this study are (i) to quantify volumes of past debris flows remaining visible on the present-day cone surface; and (ii) to assess the granulometry of deposited material. Based on these data, (iii) M–F relationships are determined for past events. In subsequent steps, (iv) the amount and type of precipitation that have led to the release of individual debris flows and (v) changes in debris-flow activity resulting from changing terrain and climatic conditions are discussed.

This article reports on M–F relationships for 62 debris flows reconstructed since A.D. 1863, leaving 229 lobes visible on the present-day surface of the cone of the Ritigraben torrent (Valais, Swiss Alps).

2. Study area

The intermediate debris-flow cone of the Ritigraben torrent (Fig. 1) is located on a structural terrace (1800–1500 masl) south of the village of Grächen (Valais, Swiss Alps, 46° 11′ N./7° 49′ E.). The structural terrace is part of a large, deep-sited sagging (Noverraz et al., 1998) and causes deposition of debris-flow material. Field evidence indicates that the cone has been in an aggradational stage over the last centuries and that erosional activity is restricted to very large, but rare, sediment bypass events.

The Ritigraben torrent originates in permafrost environments, at 2600 masl, and massive ice lenses have been observed in the frontal part of the rock–glacier tongue after the triggering of 11 debris-flow surges on 24 September 1993. Geophysical and borehole prospecting as well as BTS measurements (= bottom temperature of the winter snow cover) have since confirmed the existence of contemporary permafrost in the source area of debris flows (see Lugon and Monbaron, 1997; Stoffel et al., 2005 for details).

Previous tree-ring studies on the Ritigraben cone have focused on the reconstruction of past events. Dendrogeomorphic investigations as well as the analysis of archival data allowed for a reconstruction and documentation of 124 events for the period A.D. 1570–2008 (Stoffel et al., 2008b). For the last 300 years (A.D. 1706–2005), data indicate a mean annual frequency of 0.33 events.

The study area is located in a dry inner-alpine valley, with debris flows occurring primarily as a result of localized convective (thunderstorms) or regional advective (persistent rainfall) storm events (Stoffel et al., in review). While convective storms are most commonly observed in summer, advective storms tend to be more common in late summer and fall, when strong low-pressure systems located in the Mediterranean Sea (so-called Genoa lows) adduct wet-warm air masses toward the Alps over several days (Grebner and Roesch, 1998).

Because of the large availability of sediment in the source area (Lugon and Monbaron, 1997) and the debris-flow channel, the Ritigraben is in a transport-limited situation of sediment discharge. However, the high elevation of the source area of debris flows and the local rock glacier restrict present-day debris-flow activity to summer (June, July, and August) and early fall (September). A comparison of dendrogeomorphic reconstructions of past debris-flow events and historical data on regional flooding (Stoffel et al., 2005, 2008b) shows a clear peak in debris-flow activity in July and August (32% each) for the period A.D. 1570–2008. If only the last 50 years are taken into account, activity is largest in August and September, with almost no debris flows in early summer (June and July).

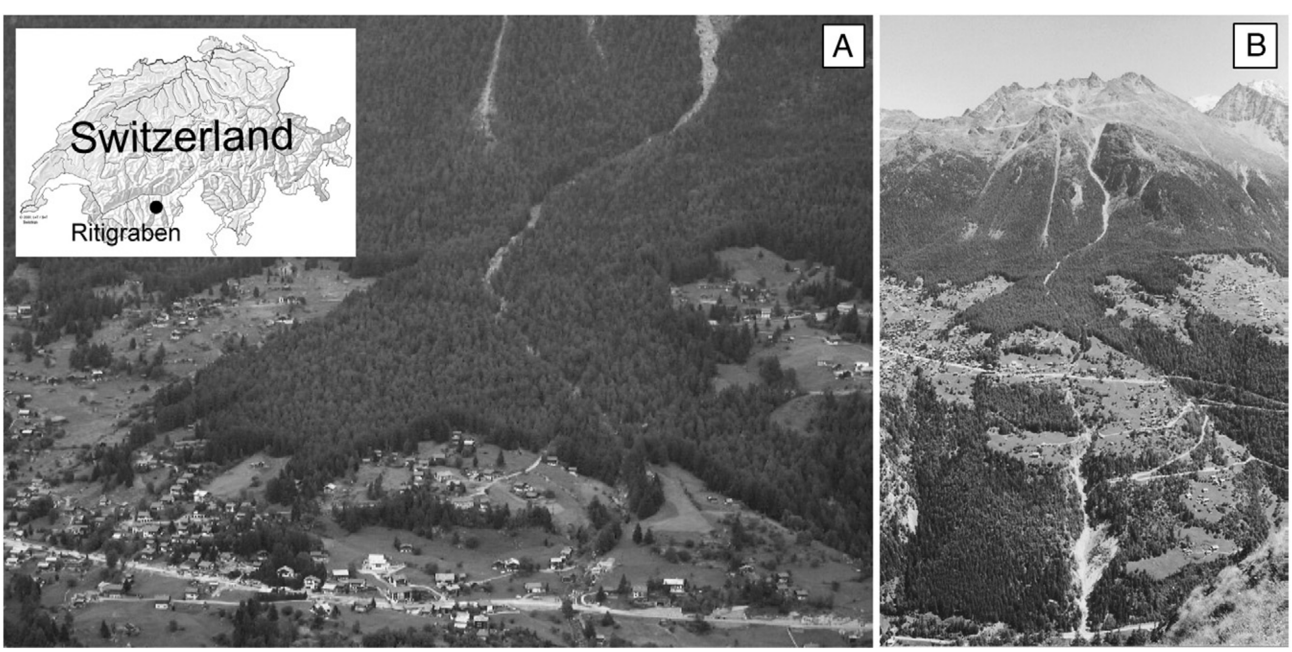


Fig. 1. The Ritigraben torrent (Valais, Swiss Alps) rises from its source at 2600 masl and passes through a forested cone located on a structural terrace near the village of Grächen before converging with the Mattervispa River (1080 masl): (A) Detail of the intermediate debris-flow cone (32 ha) and its mixed conifer stand. (B) View of the debris-flow system (catchment area: 1.36 km^2, channel lengths: 3.5 km).

Data on magnitude of past events only cover the past 15 years. While the 1994, 2002, and 2008 events mobilized 3000–5000 m^3, an estimated 60,000 m^3 were transported by 11 debris-flow surges on 24 September 1993. As a result, the debris-flow channel has been deeply scoured, with erosion depths attaining up to 4 m locally (Zimmermann et al., 1997).

3. Material and methods

3.1. Dating of deposits and attribution to specific events

The frequency of debris flows was reconstructed for the Ritigraben cone using dendrogeomorphic methods (see Stoffel and Bollschweiler, 2008, 2009). Fieldwork started with a mapping of features associated with past debris-flow activity (i.e., lobes, levees, and abandoned channels) on a scale of 1:1000. Based on an outer inspection of the stems and on their position with respect to debris-flow deposits, trees that have obviously been disturbed by past debris-flow activity were selected on the cone. In total, 1204 trees were sampled (2450 increment cores): 539 European larch (*Larix decidua* Mill.), 429 Norway spruce (*Picea abies* (L.) Karst.), and 134 cembran pine (*Pinus cembra* L.). Increment cores and crosssections of the selected trees were then analyzed and data processed following the standard procedures described in Bräker (2002). The age of lobate deposits was assessed by attributing severe growth disturbances identified in the tree-ring series to individual deposits in the field (Fig. 2). Dating of a lobe was possible (i) if a survivor tree was injured through the deposition of material; (ii) if its stem base was buried by debris; or (iii) if it was tilted. Results from the dendrogeomorphic investigation have been published by Stoffel et al. (2008b), and data from this study serve as input for the present work.

3.2. Field observations and volumes of deposits

The volume of lobate deposits identified on the present-day surface of the cone was assessed based on morphometric properties. As illustrated in Fig. 3, individual lobes were considered as truncated triangular prisms and their volume V was calculated with Eqs. (1) and (2):

$$V = 1/3(w_f + w_c + w_t) \times A \quad (1)$$

$$A = 1/2\,ab \times \sin\gamma \quad (2)$$

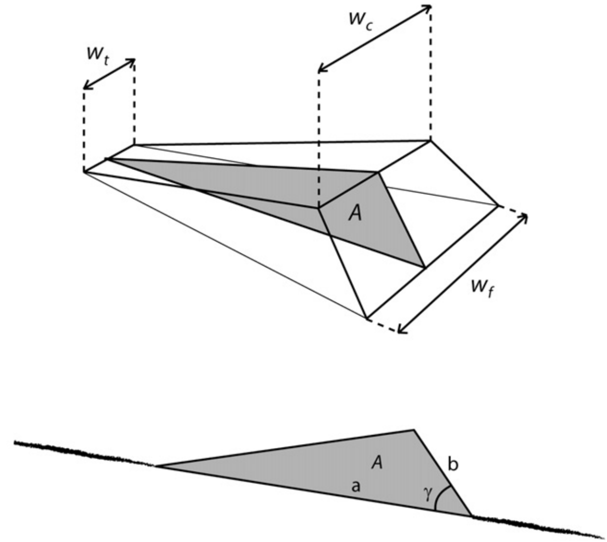


Fig. 3. Volume determination of debris-flow deposits visible on the present-day cone surface. For explanations see text and Eqs. (1) and (2).

with w_f, w_c, and w_t representing the widths at the front and crest of the debris-flow lobe and at the end of the debris-flow tail, respectively; A stands for the central triangle surface and is determined via the lobe (a) and snout (b) lengths and the slope angle of the snout (γ).

Mean (∅<0.5 m, 0.5–1 m, or 1–2 m) and maximum grain sizes (∅ 0.1, 0.5, 1, 1.5, 2, or 3 m) were measured for every lobe and lateral levee associated with a debris-flow event. Measurements were performed for at least 20 boulders per feature and always upslope of the lobe snout. Although such a sampling overestimates mean grain sizes of deposits as the finer surface sediments were removed through winnowing by rain, winds and/or overland flow (Blikra and Nemec, 1998; Blair, 1999; Gómez-Villar and García-Ruiz, 2000; de Scally and Owens, 2005), it provides a realistic image on the stream power of individual events.

3.3. Magnitude–frequency relationships of past and contemporary debris flows

While much of the field evidence typically resides on debris-flow cones (Haeberli et al., 1991), subsequent incidences may also

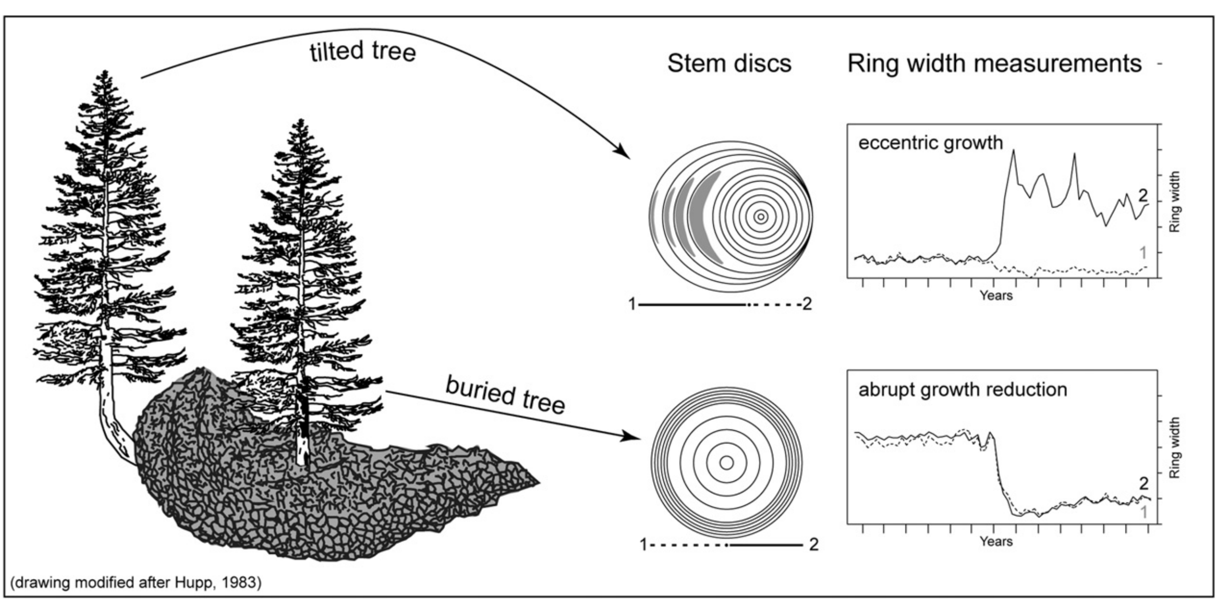


Fig. 2. Tree-ring "signatures" used to determine the age of debris-flow deposits (drawing modified after Hupp, 1983).

overprint or remove geomorphic and botanical evidence of previous events (Hupp, 1984). This is why an assessment of debris-flow magnitude which considers exclusively the deposits visible on the present-day surface will run the risk of underestimating the size of individual events.

To account for this problem, the assessment of event magnitude and M–F relationships was not only based on the first-order parameters listed above (i.e., volumetric data of lobate deposits, mean and maximum grain sizes of boulders), but also included analysis of a series of second-order surrogate variables, such as (i) snout elevations of lobes as a proxy for stream power; (ii) damage caused to the forest along the tracks and to tree survival inside lobes (given as light, medium, and dense; Hansen and Hahn, 1992) as indicators of impact energies involved; as well as (iii) the distribution of lobes and levees belonging to the same event as a proxy for the lateral spread of flows. In addition and similar to Jakob et al. (2000) or Carrara et al. (2003), we used (iv) eyewitness reports and (v) volumetric data of the most recent events (1993, 1994, 2002, and 2008) to further increase magnitude control.

Based on the above criteria, four different size classes of debris flows are presented here and given as small (*S*), medium (*M*), large (*L*), and extra large (*XL*), alluding to the debris-flow classes of the tenfold classification described by Jakob (2005). As pure descriptors of debris-flow sizes remain vague, they are attributed numbers. These values reflect the estimated magnitude of aggradational events at the cone apex, but they are not representative of events transported beyond the base of the cone during unusual episodes of erosion and sediment bypass events. The temporal frequency of events was analyzed per size class with the FHX2 software (Grissino-Mayer, 2001). This tool has been designed for fire reconstructions derived from tree-ring records, but can also be used for other types of dendrochronological time series. Parameters assessed include debris-flow frequency (incl. standard deviation), mean debris-flow intervals, Weibull median intervals, minimum and maximum debris-flow intervals as well as lower (0.125) and upper (0.875) exceedance intervals.

3.4. Meteorological records

The Federal Office of Meteorology and Climatology (MeteoSwiss, 2009) maintains a dense network of observation stations and operates a recording station in Grächen (1619 masl) located ~1.3 km north of the Ritigraben torrent. The station has been operational almost continuously since A.D. 1863, and records include data on 24-h precipitation sums, minimum, maximum, and mean temperatures as well as snow depths.

Within this study, meteorological data are used (i) to analyze the type (i.e., advective or convective) and (ii) duration (24-h resolution) of precipitation events that have led to the release of debris-flow events as well as (iii) to assess rainfall totals recorded at the meteorological station during events. In addition, the presence of antecedent rain or snow was noted as well.

4. Results

4.1. Dating and quantification of debris-flow deposits

Geomorphic mapping permitted identification of 769 features relating to debris-flow activity on the cone of the Ritigraben torrent. The features inventoried in the study area covering 32 ha included 291 lobes, 465 levees, and 13 well-developed debris-flow channels. Fig. 4 illustrates the features identified on the present-day surface of the cone and provides indications of the density of the vegetation cover. A majority of lobate deposits has predominant grain sizes <0.5 m (38%) or between 0.5 and 1 m (51%). In only 11% of the deposits, mean grain sizes exceed 1 m. The size of the largest particles per lobe, in contrast, easily surpasses 2 m, with the largest boulders >10 m^3. While survivor trees are scarce inside these bouldery deposits, they can be observed more frequently in lobes with smaller mean and maximum grain sizes as well as close to the front of deposits or toward their lateral limits.

Dendrogeomorphic analyses of trees disturbed by past debris-flow events yields evidence for 62 events between A.D. 1863 and 2008. From the 291 lobate deposits identified on the cone, 229 lobes (79%) can be attributed to particular debris flows. While 20 (7%) of the remaining lobes date back to the period 1570–1862, tree-ring records do not allow an assignment of calendar years for 42 deposits (14%). Most of the undated lobes do not support trees at all or the vegetation identified is growing on the debris-flow material.

On average, four deposits are identified per event on the cone (median: 2 deposits). For the debris-flow events of 1922 and 1987, however, tree-ring records allow dating of 26 and 23 lobes, respectively. While evidence of debris-flow activity is registered in the tree-ring series, we do not find deposits for 15 events (24%) on the present-day cone surface.

The volume of individual deposits varies by several orders of magnitude. The smallest deposits identified on the present-day surface have volumes <5 m^3 and were left on the cone by debris-flow surges with small mean grain sizes in the late nineteenth and early twentieth centuries. The largest lobe, in contrast, accounts for 3061 m^3 and was deposited in 1922. Evidence for the 1922 event is still visibly present on the current-day surface with 26 lobes totaling 13,872 m^3. The mean volume identified per event, however, remains much smaller and amounts to 1144 m^3 (median: 688 m^3). The volume of all dated deposits on the cone totals more than $7\times10^4\,m^3$. Notably, the 1994, 2002, and 2008 debris flows did not leave any deposits on the current-day surface, as they were remaining inside the main channel that was scoured up to 4 m during the 1993 events.

4.2. Characteristics of debris flows belonging to different size classes

The volumes persisting on the present-day surface of the cone, as well as data on mean and maximum grain sizes are used as first-order criteria for the assessment of debris-flow magnitude (*S*, *M*, *L*, and *XL*) but are also coupled with other surrogates to corroborate results. These surrogates include (i) the degree of tree survival inside deposits, (ii) lateral spread of flows on the cone, as well as (iii) snout elevations of lobes. The characteristics of the different debris-flow size classes are given in Table 1.

Over the last ~150 years, data indicate that more than 40% of the reconstructed debris flows (25 records) belong to *class S* events. These debris flows are characterized by comparably high snout elevations with early deposition (~1630 masl on average). Deposition of surges on the cone seems to be complete, and the spread of deposits remains very limited. *Class S* events are estimated to be 10^2–$10^3\,m^3$ in size at the level of the cone apex.

Class M debris flows are frequent at Ritigraben as well, representing approximately one-third of the incidences of the past 150 years (20 events). Fig. 5A provides an example of a *class M* deposit belonging to a debris-flow event dated to 1947 as well as the spatial distribution of 1947 deposits on the cone. *Class M* events travel slightly farther down the cone as compared to small events. Mean snout elevations are at ~1600 masl and have mean grain sizes of 0.5–1 m. Individual surges may exceptionally pass the low gradient segments of the cone and reach the valley floor at 1080 masl, but entrainment of material and spread of deposits on the cone surface remain very limited. *Class M* debris flows are estimated to be 10^3–$5\times10^3\,m^3$ in size at the cone apex.

In total, 14 large debris flows (*class L*) have occurred at Ritigraben throughout the period covered by the reconstruction. This category of debris flows exhibits mean grain sizes of boulders 0.5–1 m (Fig. 5B). Individual flows are deposited in the lower reaches of the low

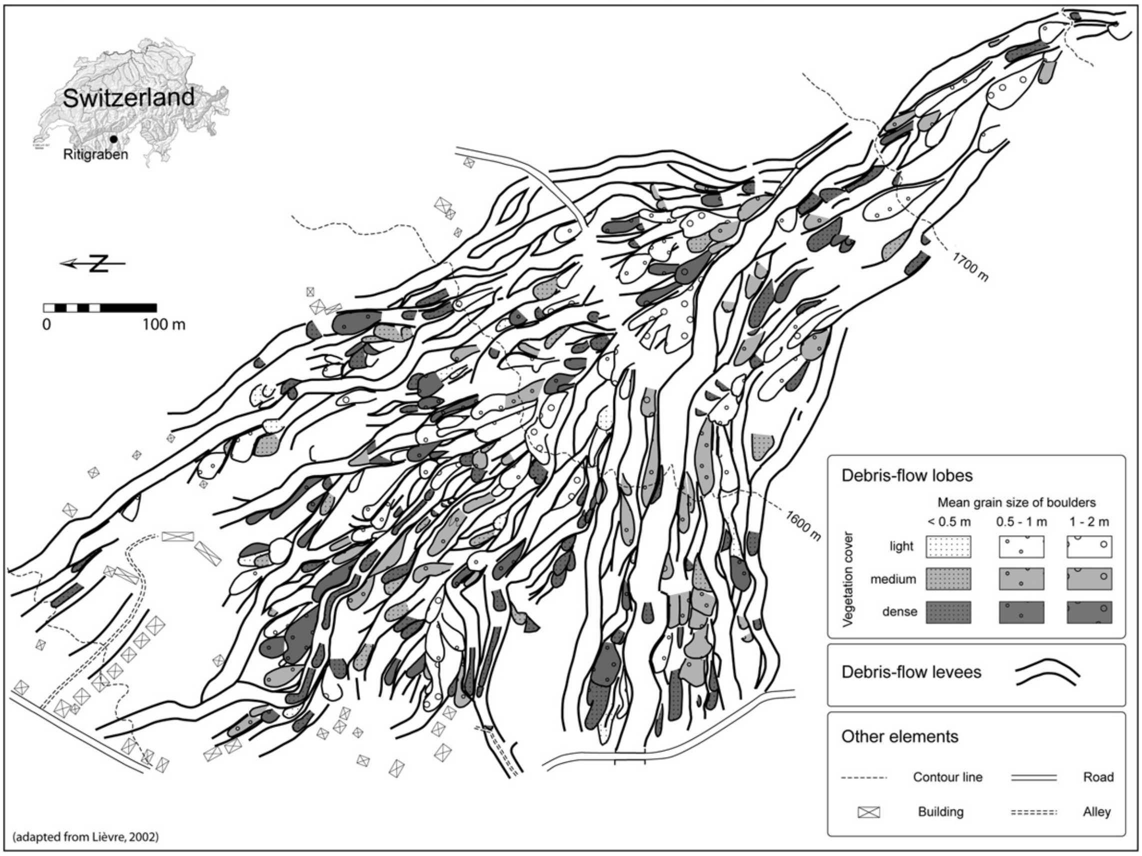


Fig. 4. Geomorphic map of the debris-flow cone with lobes, levees, and channels. The key indicates the density of the vegetation cover and the mean grain size of boulders of the lobes.

gradient segment of the cone at ~1560 masl or transported into the receiving Mattervispa during sediment bypass events. In contrast to smaller events, *class L* flows entrain material from the channel and may leave deposits in different segments of the cone. The distribution of deposits of the 1897 *class L* event is given in Fig. 5B, and the volume of this category of events is estimated to 5×10^3–$10^4\,m^3$.

The return period of *XL* events in this small watershed spans decades and only three debris-flow events of this size have been identified for the last 150 years. With mean grain sizes of 1–2 m (Fig. 5C) and volumes estimated to 10^4–$5\times10^4\,m^3$ at the cone apex, these events are considered the maximum size that can be achieved under current climatic conditions. All *XL* debris flows on record bypassed the cone and reached the valley floor, but exhibited different flow behaviors in the low gradient segments of the cone where surges either aggraded or eroded colluvium. During the oldest *XL* event on record in 1922 (Fig. 5C), very viscous and slow-flowing surges (*P. Schnydrig, verbatim*) resulted in abundant and widespread deposition of material on the cone (>13,800 m^3). In contrast, volumes delivered to the Mattervispa River presumably remained quite small. Based on eyewitness accounts and field evidence, the 1948 (*P. Schnydrig, verbatim*) and 1993 events have, in contrast, scoured the debris-flow channel by several meters. While strong evidence exists for these being *XL* events, they did only overflow and sediment during the first surge(s) and did not, therefore, leave much material on the cone.

4.3. Magnitude–frequency relationships of past and contemporary debris flows

The frequency distribution of debris-flow magnitudes is given in Fig. 6 and Table 2, indicating that *class S* (10^2–$10^3\,m^3$) and *class M*

Table 1
Characteristics of past Ritigraben debris flows (A.D. 1863–2008) based on field surveys and tree-ring records.[a]

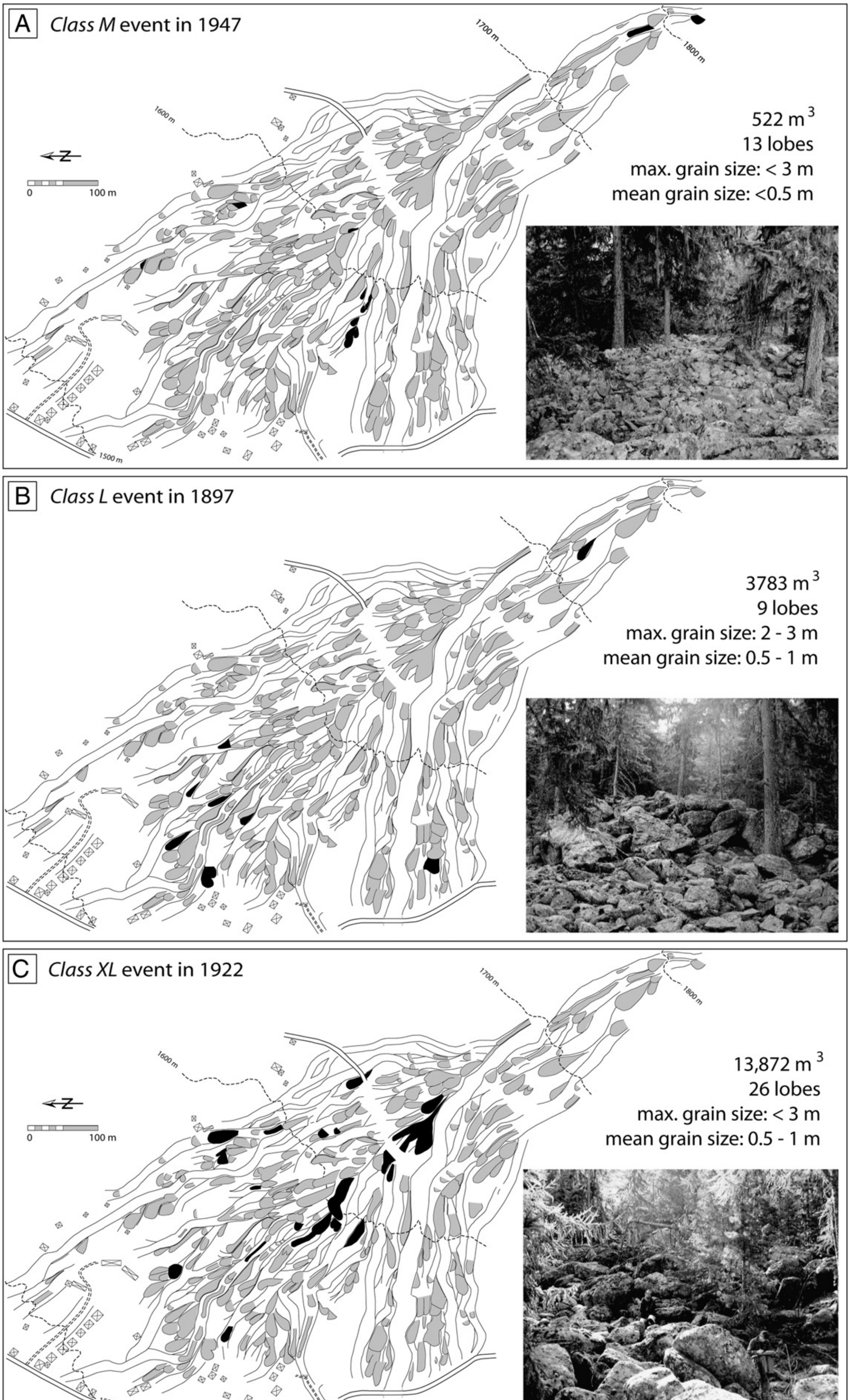
Debris-flow characteristics	*Class S*	*Class M*	*Class L*	*Class XL*
Snout elevation	1630 m	1600 m[a]	1560[a]	1080
Spread of flows on cone	Low	Low	Medium	Low/large
Deposition on cone	Complete	Almost complete	Partial	Limited
Entrainment of material	Very limited	Limited	Limited	Unlimited
Mean grain size of boulders (%) (<0.5, 0.5–1, 1–2)	60/40/0	44/54/2	36/51/14	24/51/24
Max. grain size of boulders (%) (0.1, <1, <1.5, <2, <3)	43/7/7/40/3	15/15/11/37/22	17/16/10/24/23	14/14/8/35/30
Events	25	20	14	3
Magnitude (m^3)	10^2–10^3	10^3–5×10^3	5×10^3–10^4	10^4–5×10^4

[a] Individual surges of *class M* and *L* debris may bypass the cone and reach the bottom of the valley at 1080 masl.

Table 2
Statistics of temporal frequency of debris-flow events for different magnitude classes.[a]

Temporal frequency of events	*Class S*	*Class M*	*Class L*	*Class XL*	Total
Events (no.)	25	20	14	3	62
Debris-flow frequency	0.18	0.14	0.10	–	0.42
Mean debris-flow interval (yr)	5.42	7.37	9.54	–	2.38
Weibull median interval (yr)	4.94	5.96	8.14	–	2.18
Standard deviation (yr)	3.19	6.65	6.88	–	1.49
Debris-flow interval (min., yr)	1	2	1	–	1
Debris-flow interval (max., yr)	12	27	24	–	8
Lower exceedance interval (yr)[a]	1.95	1.60	2.59	–	0.85
Upper exceedance interval (yr)[a]	9.20	14.31	17.48	–	4.09

[a] Thresholds for the lower and upper exceedances set at 0.125 and 0.875.


A Class M event in 1947
1700 m
1800 m
1600 m
N
0 100 m
1500 m
522 m 3
13 lobes
max. grain size: < 3 m
mean grain size: <0.5 m
B Class L event in 1897
3783 m 3
9 lobes
max. grain size: 2 - 3 m
mean grain size: 0.5 - 1 m
C Class XL event in 1922
1700 m
1800 m
1600 m
N
0 100 m
1500 m
13,872 m 3
26 lobes
max. grain size: < 3 m
mean grain size: 0.5 - 1 m

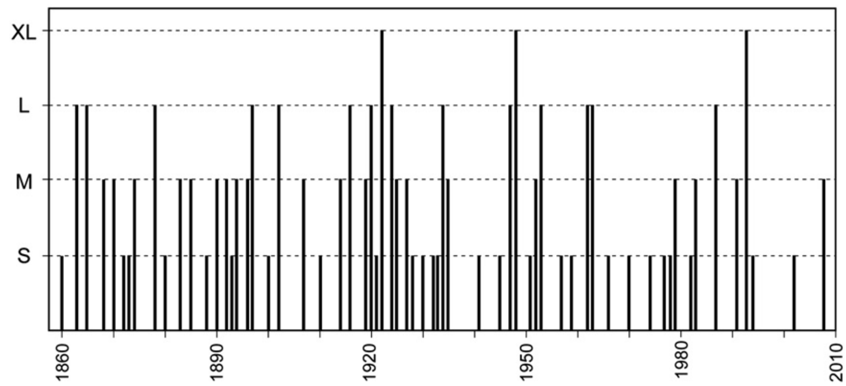


Fig. 6. Reconstructed time series of debris-flow magnitudes, in five classes, for the period from 1858 to 2008. Note the clustering of important events in the early decades of the twentieth century and the absence of *class XL* debris flows before 1922.

events (10^3–$5\times10^3\,m^3$) would encompass a very typical size range of debris flows with mean intervals of 5.42 (SD: 3.19) and 7.37 (SD: 6.65) years and Weibull median intervals of 4.94 and 5.96 years, respectively. Based on the reconstruction, *class L* debris flows (5×10^3–$10^4\,m^3$) recurred at decadal intervals (9.54 years, SD: 6.88; Weibull median interval: 8.14 years). *Class XL* events (10^4–$5\times10^4\,m^3$) could, in contrast, only be identified three times over the last 150 years. Fig. 6 also illustrates the presence of variations in the frequency of different magnitudes at Ritigraben since A.D. 1863 and a clustering of *class L* (and *XL*) events between 1916 and 1935. Another cluster of *class L* and *XL* flows occurred around 1950. Except for the 1987 and 1993 events, *class L* and *XL* events are missing in the record since the early 1960s and small events predominated over the last four decades.

5. Hydrometeorological conditions — an interpretation

Based on the results presented above, we analyze the hydrometeorological conditions that have led to the release of debris flows of different magnitudes, taking into account the (i) seasonality of events, (ii) precipitation totals (in mm), (iii) duration (24-h steps), and (iv) type (i.e., advective or convective) of rainfall events as well as (v) the hydrological conditions in the source area of debris flows (see Table 3).

Class S debris flows are typically released during short-lasting, convective precipitation events (i.e., summer thunderstorms). Mean precipitation sums recorded at the meteorological station total 26 mm (min. 10 mm, max. 52 mm). The limited availability of water chiefly limits the amount of material triggered from the source area of debris flows and the diameter of mean grain size (<0.5 m). As a further result, rapid drainage usually occurs on the colluvial deposits of the cone, encouraging early deposition of material and an absence of channel scouring in the low gradient segments of the torrent on the cone. Antecedent rain (19%) and rain-on-snow events (4%) influence the triggering of debris flows but are considered less important in the bouldery, steep, and well-delimited initiation zone as compared to vegetation-mantled, nonpermafrost source areas. In contrast, the presence of frozen ground and a thin active layer early in summer allow for *class S* debris flows to be released by rainfall totals well below 20 mm. *Class S* events are most common in July and August, but can be observed in September as well.

The downslope transport of *class M* debris flows with mean grain sizes of 0.5–1 m is frequently hampered by limited precipitation amounts as well. Mean precipitation sums recorded at Grächen total 27 mm (min. 12 mm and max. 50 mm) and are very much comparable to those observed during *class S* events. *Class M* debris flows are triggered by local thunderstorms in summer (JJA) and in September, with a clear peak in activity in July and August.

During *class L* events, larger amounts of water are normally available (mean: 51 mm, min. 21 mm, and max. 179 mm). Although they have been observed from June through September, a clear peak of *class L* activity is observed in August when advective precipitation favors the release of unconsolidated debris from the active layer of the local rock glacier.

As a result of their occurrence in late summer and early fall, sediment supply from the rock glacier is not a major limiting factor for *class XL* debris-flow events, and large active-layer failures are associated with this size of event. Exclusively triggered by extensive advective rainfall (49, 100 and 116 mm of rainfall in 1922, 1948, and 1993, respectively) over several days, released volumes of *class XL* events and their capacity to transport large boulders are controlled primarily by hydroclimatic conditions rather than by sediment availability.

6. Discussion

In the study reported here, M–F relations of debris flows are assessed on the cone of the Ritigraben torrent (Swiss Alps) for the last ~150 years (1863–2008). While the reconstruction of frequencies considered growth anomalies in century-old conifers, the assessment of magnitude was based on field surveys and grain sizes of deposits, eyewitness reports, and detailed data from recent events as well as on surrogate variables, such as lateral spread and snout elevations of surges on the cone.

Despite the practical and theoretical utility of M–F relationships, serious obstacles to obtaining such data and M–F relationships exist and relations have been addressed explicitly in a very limited number of studies to date (e.g., Innes, 1985; Osterkamp et al., 1986; Ohmori and Hirano, 1988; Scott, 1989; Johnson et al., 1991). These studies either based their M–F assessments on rather limited data sets on past events, a vague description of magnitude, or a determination of magnitude at a regional level (van Steijn, 1996). However, as Strunk (1991) pertinently emphasizes, local factors are greatly influencing M–F relations, and data sets from neighboring torrential systems cannot necessarily be compared with each other. As the need for information on debris-flow magnitude has often been motivated by disasters calling for engineering solutions (Jakob, 1996), channel parameters and other factors related to debris flows have been used to determine magnitude in areas without data on past activity, such as basin area, (fan) slope, channel length, channel width or hypsometry (VanDine, 1985).

Fig. 5. Minimum lateral spread and snout elevations of lobes of (A) the *class M* debris flow of 1947 (mean particle size: 0.5–1 m), (B) the *class L* debris flow of 1897 (mean particle size: 0.5–1 m), and (C) the *class XL* debris flow of 1922 (mean particle size: 1–2 m).

Table 3
Hydrometeorological conditions observed during debris-flow events at Ritigraben since A.D. 1863.

Characteristics	S	M	L	XL
Precipitation type	Convective	Convective	Adv./conv.	Advective
Precipitation totals (mean)	26 mm	27 mm	51 mm	88 mm
Precipitation totals (max)	10 mm	12 mm	21 mm	49 mm
Precipitation totals (min)	52 mm	50 mm	179 mm	116 mm
Duration of rainfall event	<24 h	<24 h	<24–96 h	48–72 h
Seasonality[a]	**J**AS	J**JA**S	J**JA**S	A**S**
Particle sizes (Ø)	<0.5 m	0.5–1 m	0.5–1 m	1–2 m
Magnitude (m^3)	**10^2–10^3**	**10^3–5×10^3**	**5×10^3–10^4**	**10^4–5×10^4**

[a] JJAS stands for June, July, August, and September; bold letters indicate peak in activity.

Data of this study represent, in contrast, an unusually complete and probably unique record on M–F relationships covering almost 150 years of debris-flow history with a large number of debris-flow events. Identification of common debris-flow sizes and transport characteristics in the transit zone are of paramount importance for the design of torrent control, a realistic assessment of volumes deposited, or the delineation of hazard zones. While this study emphasizes that a coupling of tree-ring records with field surveys can be used to draw a very detailed envelope for the debris-flow activity of the recent past and allows for climate control, data clearly lack higher predictive power for the identification of rare and very rare events with return periods of 10^3 or 10^4 years, such as recently illustrated by Jakob and Friele (2010). Another possible limitation of the approach lies in the fact that (i) more recent events may overprint or erode evidence of former activity; (ii) small events may stall inside the channel without leaving deposits on the cone, and that (iii) the rare, but large events of 1922, 1948, and 1993 may have reset the debris-flow system. However, as the cone of the Ritigraben torrent lies on a large structural terrace formed by a large sagging, it has been in an aggradational stage over the last centuries with erosion being limited to exceptionally large, but rare, sediment bypass events. Based on field evidence and the tree-ring records, we are also confident that the large sediment bypass events did neither influence our reconstruction nor reset the debris-flow system.

Data also indicate that debris flows occur more frequently at Ritigraben as compared to neighboring catchments of the valley (Bollschweiler and Stoffel, in review; Bollschweiler et al., 2008; Sorg et al., in press) or in other regions of the European Alps (Strunk, 1991; Baumann and Kaiser, 1999; Helsen et al., 2002). Nevertheless, the period of largely increased debris-flow activity observed at Ritigraben in the early decades of the twentieth century apparently exists in other catchments of the wider study region and in the French Alps as well (Van Steijn, 1996; Bollschweiler et al., 2008). In the Italian Dolomites, in contrast, Strunk (1991) reported that torrents originating in nonpermafrost environments exhibit no significant changes in activity for the last 125 years but higher frequencies during the Little Ice Age when the release of debris flows at Ritigraben and other torrents with high elevation source areas was regularly hampered by the presence of permafrost ice or repeated snowfalls during summer precipitation events (Stoffel and Beniston, 2006).

As a result of the small size of the watershed (<5 km^2) at Ritigraben, magnitudes of debris flows differ from the tenfold classification suggested by Jakob (2005), as the present study does not provide data on very rare events but allows for a more subtle differentiation of volumes transported by debris flows with shorter return intervals. In addition, apparently, the maximum size of *class XL* events would not exceed $5\times10^4 m^3$ under current climatic conditions, which is in agreement with findings of Helsen et al. (2002) who assessed lichen-based M–F relations for 14 debris flows in the Chalance torrent (French Alps) since the early nineteenth century.

Debris-flow frequency and magnitude are functions of hydroclimatic controls (e.g., Caine, 1980; Keefer et al., 1987; Guzzetti et al., 2008) and terrain variables (Hungr et al., 1984; Crosta and Frattini, 2004; Jakob et al., 2005; Gregoretti and Dalla Fontana, 2008; Mao et al., 2009). At Ritigraben, the permafrost body located in the source area of debris flows not only controls the release and ensuing magnitude of debris flows, but also causes temporal differences in sediment availability. In contrast to hydrological events, the probability of a debris flow of a given magnitude does not remain constant through time, as *class XL* debris flows may only occur in late summer or early fall when (i) debris availability is not limited by the active layer of the rock glacier, (ii) runoff is drained by the ice surface of the permafrost body, and (iii) heavy precipitation events are most common. In contrast to other regions where frequency and magnitude of flows are controlled by the amount of regolith production (Innes, 1985), the channel is not depleted after an event. This is why sediment supply cannot be considered a limiting factor at Ritigraben, and entrainment of material will depend on limitations in stream power and on the ability of a flow to scour the channel.

With the projected climatic change, changes in the magnitude or frequency of debris flows are likely to occur. Based on the data of past events, such a change of debris-flow magnitude has been observed since A.D. 1922 when an active-layer failure was most probably responsible for the first *class XL* debris flow in centuries. Similar *XL* events in 1948 and 1993 seemed to be the result of a combination of warming summer temperatures and exceptional precipitation events as well (Pfister, 1999). Ongoing climatic change is thought to further destabilize steep rock–glacier bodies within the belt of permafrost through the melting of interstitial ice or through the surging of rock–glacier bodies (Jackson et al., 1987; Harris et al., 2009). These modifications will ultimately exert control on debris-flow volume released from the source area of debris flows, and that we will soon observe "*XXL*" events with volumes surpassing $5\times10^4 m^3$ at the cone apex at Ritigraben. Such a change in debris-flow size is even more probable as Regional Climate Model (RCM) projections suggest that the probability of occurrence of intense advective rainfalls could increase in future falls (Stoffel and Beniston, 2006), i.e., at the time of the year when sediment supply limitations are smallest. In addition, model projections also suggest a decrease in heavy summer rainfall events, which would presumably lead to a reduction of the overall frequency of events (Stoffel et al., 2008b), but leaving more time for debris-flow material to accumulate in the channel.

The debris-flow cone of the Ritigraben torrent is of Holocene age and was formed since the retreat of the valley glacier some ~10,000 years ago (Furrer, 2001). With a cone volume of ~$4.3\times10^6 m^3$, there must have been periods in the past with more frequent or larger aggradational debris flows in the Ritigraben torrent. We could speculate that larger-than-today magnitudes could have occurred shortly after glacier unloading and during periods of the Holocene with favorable climatic conditions, such as the Roman optimum or the Medieval warm period (e.g., Bradley et al., 2003). As a matter of fact, M–F relationships are not stationary, and the *XL* events observed in this study probably represent medium frequency–medium magnitude events (Leopold and Maddock, 1953; Wolman and Miller, 1960) when taking the entire post-glacial history as the reference period. "Silent witnesses" in the field, such as boulder lobes or remnants of channels located at some distance of the currently active areas of the cone, testify to the existence of such prehistoric events.

The magnitude estimates presented here reflect the sediment volume that is transported at least to the cone apex. *Class S* and most of the *class M* debris flows stall within the channel or on the cone surface at ~1630–1600 masl and do not attain the valley floor (1080 masl). *Class L* and *XL* events, in contrast, regularly bypass the low gradient segments of the cone and reach the receiving Mattervispa River. As the Ritigraben channel is incised in important debris-flow and talus slope deposits, it guarantees a large availability of poorly sorted, unconsolidated colluvium and allows the entrainment of large amounts of sediments. As a result and provided that water and/or sediment availability are not limiting factors, the size of individual *class L* and *class XL* events may increase in size by up to one order of magnitude on the cone and transport almost $10^5 m^3$ to the confluence of the Ritigraben torrent with the Mattervispa River. While the *class S* and *M* events are important in terms of long-term debris transport from the source area of debris flows and aggradation on the cone, clearly the *class L* and *XL* events are playing the primordial role in the transport of sediment into the Mattervispa River system.

7. Conclusions

Dendrochronology has proved to be a very reliable method to establish a debris-flow frequency and related magnitudes on a local scale in a mountain environment with low precipitation amounts and the presence of a perennially frozen ground in the source area of debris flows. Although the quality and quantity of the data set presented is one of the most comprehensive compiled worldwide to date, the nature of the data does not allow for a formal application of extreme value frequency analysis as commonly used for perennial streams in hydrology. This is because debris flows exhibit an episodic rather than continuous behavior and are not usually monitored. Nevertheless, this study shows, for the first time, that the nonstationarity of climatic variables chiefly influences the frequency of debris flows and that the magnitude of events at this high elevation site subsequently undergoes changes with time as well. Also changes in magnitude similar to those observed since the early twentieth century will continue to occur in a warmer greenhouse climate, and the size of individual events might attain volumes that would not have been possible during the past few centuries.

Acknowledgements

This work has been undertaken partly in the context of the following projects: EU-FP7 project ACQWA (project no. GOCE-20290), and FOEN-SFP-SRCE project RUFINE (project no. 0931030100RA0000008253). This study considerably benefited from the critical comments of Fritz Schlunegger, Michelle Bollschweiler, and two anonymous reviewers as well as from substantial contributions of Delphine Conus, Michael A. Grichting, Igor Lièvre, and Gilles Maître during fieldwork and sample analysis.

References

Baumann, F., Kaiser, K.F., 1999. The Multetta debris fan, eastern Swiss Alps: a 500-year debris flow chronology. Arct. Alp. Res. 31, 128–134.
Bezzola, G.R., Hegg, C. (Eds.), 2007. Ereignisanalyse Hochwasser 2005. Teil 1 - Prozesse, Schäden und erste Einordnung. Bundesamt Umwelt BAFU and Eidg. Forsch'anst. WSL, Bern, Birmensdorf, Switzerland. 215 pp. (in German).
Blair, T.C., 1999. Sedimentology of the debris-flow dominated Warm Spring Canyon alluvial fan, Death Valley, California. Sedimentology 46, 941–957.
Blair, T.C., McPherson, J.G., 1998. Recent debris flow processes and resultant form and facies of the Dolomite alluvial fan, Owens Valley, California. J. Sediment. Res. 68, 800–818.
Blikra, L.H., Nemec, W., 1998. Postglacial colluvium in western Norway: depositional processes, facies and paleoclimatic record. Sedimentology 45, 909–959.
Bloetzer, W., Stoffel, M., 1998. Klimawandel als Herausforderung für die Raumplanung der Vispertäler. In: Bloetzer, W., Egli, T., Petrascheck, A., Sauter, J., Stoffel, M. (Eds.), Klimaänderungen und Naturgefahren in der Raumplanung — Methodische Ansätze und Fallbeispiele, vdf Hochschulverlag AG, Zürich, pp. 127–200 (in German).
Bollschweiler, M., Stoffel, M., in review. Variations in debris-flow occurrence in an Alpine catchment — reconstruction and implications for the future. Global Planet. Change.
Bollschweiler, M., Ehmisch, M., Stoffel, M., Monbaron, M., 2007. Reconstructing spatio-temporal patterns of debris-flow activity with dendrogeomorphological methods. Geomorphology 87, 337–351.
Bollschweiler, M., Stoffel, M., Schneuwly, D.M., 2008. Dynamics in debris-flow activity on a forested cone — a case study using different dendroecological approaches. Catena 72, 67–78.
Bovis, M.J., Jakob, M., 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Processess Landf. 24, 1039–1054.
Bradley, R.S., Hughes, M.K., Diaz, H.F., 2003. Climate in medieval time. Science 302, 404–405.
Bräker, O.U., 2002. Measuring and data processing in tree-ring research — a methodological introduction. Dendrochronologia 20, 203–216.
Bundesamt für Wasser und Geologie (BWG), 2002. Hochwasser 2000 — Les crues 2000. Berichte des Bundesamtes für Wasser und Geologie, Serie Wasser 2, 1–248 (in German).
Caine, N., 1980. The rainfall intensity–duration control of shallow landslides and debris flows. Geogr. Ann. 62A, 23–27.
Carrara, A., Crosta, G., Frattini, P., 2003. Geomorphological and historical data in assessing landslide hazard. Earth Surf. Processes Landf. 28, 1125–1142.
Crosta, G.B., Frattini, P., 2004. Controls on modern alluvial fan processes in the central Alps, northern Italy. Earth Surf. Processes Landf. 29, 267–293.
de Scally, F.A., Owens, I.F., 2005. Depositional processes and particle characteristics on fans in the Southern Alps, New Zealand. Geomorphology 69, 46–56.
Eaton, L.S., Morgan, B.A., Kochel, R.C., Howard, A.D., 2003. Quaternary deposits and landscape evolution in the central Blue Ridge of Virginia. Geomorphology 56, 139–154.
Furrer, G., 2001. Alpine Vergletscherung vom letzten Hochglazial bis heute. Franz Steiner Verlag. 49 pp. (in German).
Gómez-Villar, A., García-Ruiz, J.M., 2000. Surface sediment characteristics and present dynamics in alluvial fans of the central Spanish Pyrenees. Geomorphology 34, 127–144.
Grebner, D., Roesch, T., 1998. Flächen-Mengen-Dauer-Beziehungen von Starkniederschlägen und mögliche Niederschlagsgrenzwerte im Raum der Schweiz, vdf Hochschulverlags AG, Zürich, Switzerland. 190 pp. (in German).
Gregoretti, C., Dalla Fontana, G., 2008. The triggering of debris flow due to channel-bed failure in some alpine headwater basins of the dolomites: analyses of critical runoff. Hydrol. Process. 22, 2248–2263.
Grissino-Mayer, H.D., 2001. FHX2 — software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Res. 57 (1), 115–124.
Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5, 3–17.
Habersack, H., Krapesch, G., 2006. Hochwasser 2005 — Ereignisdokumentation der Bundesbauverwaltung, des Forsttechnischen Dienstes für Wildbach- und Lawinenverbauung und des Hydrographischen Dienstes, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien. 157 pp. (in German).
Haeberli, W., Rickenmann, D., Zimmermann, M., Rösli, U., 1991. Murgänge, Mitt. Bundesamt Wasserwirtsch. 4, 77–88 (in German).
Hansen, M.H., Hahn, J.T., 1992. Determining stocking, forest type, and stand-size class from forest inventory data. Northern J. Appl. For. 9, 82–89.
Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M.A., Lehning, M., Matsuoka, N., Murton, J.B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., 2009. Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. Earth-Sci. Rev. 92, 117–171.
Helsen, M.M., Koop, P.J.M., van Steijn, H., 2002. Magnitude–frequency relationship for debris flows on the fan of the Chalance torrent, Valgaudemar (French Alps). Earth Surf. Processes Landf. 27, 1299–1307.
Hungr, O., Morgan, G.C., Kellerhals, R., 1984. Quantitative analysis of debris torrent hazard for design of remedial measures. Can. Geotech. J. 21, 663–677.
Hungr, O., McDougall, S., Bovis, B., 2005. Entrainment of material by debris flows. In: Jakob, M., Hungr, O. (Eds.), Debris Flow Hazard and Related Phenomena. Springer, Heidelberg, Berlin, pp. 135–158.
Hungr, O., McDougall, S., Wise, M., Cullen, M., 2008. Magnitude–frequency relationships of debris flows and debris avalanches in relation to slope relief. Geomorphology 96, 355–365.
Hupp, C.R., 1983. Geo-botanical evidence of late Quaternary mass wasting in block field areas of Virginia. Earth Surf. Processess Landf. 8, 439–450.
Hupp, C.R., 1984. Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California. Environ. Geol. Water Sci. 6, 121–128.
Innes, J.L., 1983. Lichenometric dating of debris-flow deposits in the Scottish Highlands. Earth Surf. Processess Landf. 8, 579–588.
Innes, J.L., 1985. Magnitude–frequency relations of debris flows in northwest Europe. Geogr. Ann. 67A, 519–524.
Iverson, R.M., 1997. The physics of debris flows. Rev. Geophys. 35, 245–296.
Jackson, L.E., Kostaschuck, R.A., MacDonald, G.M., 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. Rev. Eng. Geol. 7, 115–124.
Jakob, M., 1996. Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia. Ph.D. dissertation, University of British Columbia at Vancouver, Vancouver, BC, Canada, 232 pp.
Jakob, M., 2005. A size classification for debris flows. Eng. Geol. 79, 151–161.
Jakob, M., Friele, P., 2010. Frequency and magnitude of debris flows on Cheekye River, British Columbia. Geomorphology 114 (3), 382–395.
Jakob, M., Hungr, O., 2005. Debris Flow Hazard and Related Phenomena. Springer, Heidelberg, Berlin. 739 pp.
Jakob, M., Hungr, O., Anderson, D., Fuller, T., Ayotte, D., 2000. The July 7, 1997 debris flow at Hummingbird Creek. Can. Geotech. J. 37, 1109–1125.
Jakob, M., Bovis, M., Oden, M., 2005. The significance of channel recharge rates for estimating debris-flow magnitude and frequency. Earth Surf. Processess Landf. 30, 755–766.
Johnson, P.A., McCuen, R.H., Hromadga, T.V., 1991. Magnitude and frequency of debris flows. J. Hydrol. 123, 68–82.
Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Brown, W.M., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., Zatkin, R.S., 1987. Real-time landslide warning during heavy rainfall. Science 238, 921–925.
Leopold, L.B., Maddock Jr., T., 1953. The hydrologic geometry of stream channels and some physiographic implications. U. S. Geol. Surv. Prof. Pap. 282-B, 39–85.
Lugon, R., Monbaron, M., 1997. Stabilité des terrains meubles en zone de pergélisol et changements climatiques. Deux études de cas en Valais: Le Ritigraben (Mattertal) et la moraine du Dolent (Val Ferret). Zürich: vdf Hochschulverlag AG, Zürich, Switzerland, 101 pp. (in French).

Mao, L., Cavalli, M., Comiti, F., Marchi, L., Lenzi, M.A., Arattano, M., 2009. Sediment transfer processes in two Alpine catchments of contrasting morphological settings. J. Hydrol. 364, 88–98.
Marchi, L., D'Agostini, V., 2004. Estimation of debris-flow magnitude in the eastern Italian Alps. Earth Surf. Processess Landf. 29, 207–220.
McArdell, B.W., Bartelt, P., Kowalski, J., 2007. Field observations of basal forces and fluid pore pressure in a debris flow. Geophys. Res. Lett. 34, L07406.
MeteoSwiss, 2009. Swiss Meteorological Office. www.meteoschweiz.ch (site last visisted May 13, 2009).
Noverraz, F., Bonnard, C., Dupraz, H., Huguenin, L., 1998. Grands glissements de terrain et climat. Versinclim — comportement passé, présent et futur des grands versants instables subactifs en fonction de l'évolution climatique, et évolution en continue des mouvements en profondeur, vdf Hochschulverlags AG, Zürich, Switzerland, 265 pp. (in French).
Ohmori, H., Hirano, M., 1988. Magnitude, frequency and geomorphological significance of rocky mud flows, landcreep and the collapse of steep slopes. Z. Geomorphol. N. F. Suppl.bd 67, 55–65.
Osterkamp, W.R., Hupp, C.R., Blodgett, J.C., 1986. Magnitude and frequency of debris flows, and areas of hazard on Mount Shasta, Northern California. U. S. Geol. Surv. Prof. Pap. 1396-C, 1–20.
Pfister, C., 1999. Wetternachhersage. Paul Haupt Verlag, Bern, Stuttgart, Wien. 304 pp. (in German).
Pierson, T.C., 1980. Erosion and deposition by debris flows at Mt. Thomas, north Canterbury, New Zealand. Earth Surf. Processes 5, 227–247.
Rapp, A., Nyberg, R., 1981. Alpine debris flows in northern Scandinavia. Geogr. Ann. 63A, 183–196.
Rickenmann, D., 1999. Empirical relationships for debris flows. Nat. Hazards 19, 47–77.
Rickenmann, D., Zimmermann, M., 1993. The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology 8, 175–189.
Scheidl, C., Rickenmann, D., Chiari, M., 2008. The use of airborne LiDAR data for the analysis of debris flow events in Switzerland. Nat. Hazards Earth Syst. Sci. 8, 1113–1127.
Scott, K.M., 1989. Magnitude and frequency of lahars and lahar runout flows in the Toutle–Cowlitz River System. U.S. Geol. Surv. Open-File Rep, pp. 90–385. 106 pp.
Sorg, A., Bugmann, H., Bollschweiler, M., Stoffel, M., in press. Debris-flow activity along a torrent in the Swiss Alps: minimum frequency of events and implications for forest dynamics. Dendrochronologia.
Stoffel, M., Beniston, M., 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophys. Res. Lett. 33, L16404.
Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research — an overview. Nat. Hazard Earth Syst. Sci. 8, 187–202.
Stoffel, M., Bollschweiler, M., 2009. What tree rings can tell about earth–surface processes. Teaching the principles of dendrogeomorphology. Geogr. Compass 3, 1013–1037.
Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gärtner, H.W., Monbaron, M., 2005. 400 years of debris flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arct. Antarc. Alp. Res. 37, 387–395.
Stoffel, M., Bollschweiler, M., Hassler, G.R., 2006. Differentiating events on a cone influenced by debris-flow and snow avalanche activity — a dendrogeomorphological approach. Earth Surf. Processess Landf. 31, 1424–1437.
Stoffel, M., Bollschweiler, M., Leutwiler, A., Aeby, P., 2008a. Large debris-flow events and overbank sedimentation in the Illgraben torrent (Valais Alps, Switzerland). Open Geol. J. 2, 18–29.
Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Maître, G., 2008b. Unraveling the patterns of late Holocene deposition processes and channel incision on a debris-flow cone in the Swiss Alps: chronology, environment and implications for the future. Global Planet. Change 60, 222–234.
Stoffel, M., Bollschweiler, M., Beniston, M., in review. Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences — potential future evolutions. Clim. Change.
Strunk, H., 1991. Frequency distribution of debris flows in the Alps since the 'Little Ice Age'. Z. Geomorph. Suppl. Bd. 83, 71–81.
Strunk, H., 1997. Dating of geomorphological processes using dendrogeomorphological methods. Catena 31, 137–151.
Van Steijn, H., 1996. Debris-flow magnitude–frequency relationships for mountainous regions of central and northwest Europe. Geomorphology 15, 259–273.
VanDine, D.F., 1985. Debris flows and debris torrents in the southern Canadian Cordillera. Can. Geotech. J. 22, 44–67.
Wolman, M.G., Miller, W.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 68, 54–74.
Zimmermann, M., Mani, P., Romang, H., 1997. Magnitude–frequency aspects of alpine debris flows. Eclogae Geol. Helv. 90, 415–420.